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Why have supersymmetric particles not been observed?

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ABSTRACT

If low-energy supersymmetry is the solution to the hierarchy problem, it is a puzzle why supersymmetric particles have not been observed experimentally to date. We show that supersymmetric particles in the TeV region can be explained if the fundamental cut-off scale of the theory is smaller than the 4-dimensional Planck scale and if thermal leptogenesis is the source of the observed baryon asymmetry. The supersymmetric particles such as sfermions and gauginos are predicted to be in the TeV region, while the gravitino is the LSP with mass of $O(100)$ GeV and is a good candidate for dark matter. Interestingly, the cosmological moduli problem can be solved in the theory with the low cut-off scale.

Supersymmetry (SUSY) has been known as the most plausible candidate for the theory beyond the standard model (SM). If low-energy SUSY is indeed the solution to the hierarchy problem, then the masses of SUSY particles such as squarks, sleptons and gauginos are naively of $O(100)$ GeV or so, and we would expect to already be seeing evidence of these particles. However, the SUSY particles have not been observed experimentally to date, which pushes the SUSY scale beyond the expected value. In fact, in the minimal supersymmetric standard model (MSSM), large soft SUSY breaking masses of $O(1)$ TeV are typically required in order to avoid conflict with the LEP bound on the light Higgs boson mass. This already implies that the solution to the hierarchy problem is not the major reason for the low-energy SUSY. If the characteristic SUSY scale is indeed in the TeV region, there must be another reason for the presence of the low-energy SUSY at the TeV scale, since otherwise the SUSY is likely broken at a higher scale in the landscape [1].

In this Letter we argue that the TeV scale SUSY can be understood in a theory with a cut-off scale, Λ, one order of magnitude lower than the Planck scale M_p, if thermal leptogenesis [2] is the source of the observed baryon asymmetry. As noted in Ref. [3], the cosmological moduli problem [4,5] can be beautifully solved in this framework, using the solution proposed long ago by Linde [6]. Our theoretical framework has interesting implications for collider experiments, dark matter search experiments, and inflation models, which we shall describe below.

Let us consider the SUSY mass spectrum. We assume gravity-mediated SUSY breaking and introduce a pseudomodulus S, which has a non-vanishing F-term,

$$|F_S| = \sqrt{3} m_{3/2} M_p, \tag{1}$$

where we have required the vanishingly small cosmological constant. Given that the fundamental cut-off scale of the theory is Λ, any non-renormalizable operators should be suppressed by some powers of Λ. Then the scalars acquire a mass from

$$\mathcal{L} = -\int d^4\theta \, \frac{S^\dagger S Q^\dagger Q}{\Lambda^2}, \tag{2}$$

where Q collectively denotes the matter fields in the visible MSSM sector. The MSSM gauginos acquire a mass from

$$\mathcal{L} = -\int d^2\theta \, \frac{S}{\Lambda} W_\alpha W_\alpha, \tag{3}$$

where W_α is a chiral superfield for the MSSM gauge multiplets. The scalar and gaugino masses are therefore given by

$$m_0 \sim m_{1/2} \sim m_{3/2} \frac{M_p}{\Lambda}. \tag{4}$$

The gravitino is generally lighter than the sfermion and the gauginos, if the cut-off scale Λ is lower than the Planck scale. As we shall see below, Λ must be one order of magnitude smaller than the Planck scale to solve the cosmological moduli problem. Thus, the gravitino is the lightest SUSY particle (LSP), and is a good candidate for dark matter. The little hierarchy between the soft SUSY breaking masses and the gravitino mass is one of the important results in this Letter.

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The gravitinos are produced by particle scatterings in thermal plasma, and its abundance depends on the reheating temperature of the Universe [7–10]

$$Y_{3/2} \simeq 1 \times 10^{-13}\left(1+\frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)\left(\frac{T_R}{10^9\ \text{GeV}}\right), \tag{5}$$

where $m_{\tilde{g}}$ is the gluino mass evaluated at the reheating, T_R denotes the reheating temperature, and we considered only the SU(3) contribution to the gravitino production. Using (4), the gravitino density parameter is expressed by

$$\Omega_{3/2}h^2 \simeq 0.1c_3^2\left(\frac{m_{3/2}}{100\ \text{GeV}}\right)\left(\frac{\Lambda}{0.1M_p}\right)^{-2}\left(\frac{T_R}{10^9\ \text{GeV}}\right), \tag{6}$$

where we have defined the gluino mass as $m_{\tilde{g}} = c_3 m_{3/2} M_p/\Lambda$ with $c_3 = O(1)$, and we dropped the contribution of the transverse component of the gravitino. Let us presume that thermal leptogenesis is the source of the observed baryon asymmetry. Then successful thermal leptogenesis requires $T_R \gtrsim 10^9$ GeV [11,12]. Combined with (6), the upper bound of the gravitino mass is then fixed to be about 100 GeV in order to account for the dark matter abundance, $\Omega_{DM}h^2 = 0.1123 \pm 0.0035$ [13]. The SUSY breaking mass scale can be pushed into the TeV region in order to account for the observed baryon asymmetry and dark matter abundance (see Eq. (4)). This explains why the SUSY particles have not been observed experimentally to date, if the SUSY is preferentially broken at a high scale [1]. (See note added for another argument.) We emphasize here that the requirement of thermal leptogenesis plays an essential role in the above argument.

Next let us briefly show how the moduli problem can be solved; see Ref. [3] and references therein for details. If the theory has a fundamental cut-off scale Λ, there is generically the following quartic coupling,

$$\mathcal{L} = -\int d^4\theta\, \frac{\chi^\dagger \chi Z^\dagger Z}{\Lambda^2}, \tag{7}$$

where Z represents the modulus (including S), and χ denotes a chiral superfield which dominates the energy density of the Universe when Z starts to oscillate. In the standard scenario, the χ is identified with the inflaton. If $\Lambda \sim 0.1M_p$, the modulus has a mass of $O(10)H$, where H is the Hubble parameter, then the modulus Z follows the time-dependent minimum and amplitude of coherent oscillations is exponentially suppressed [6]. Thus, the cosmological moduli problem is solved. This solution requires Λ to be smaller than or equal to $0.1M_p$. In order not to affect the successful grand unification, we consider $\Lambda \sim 0.1M_p$ in this Letter.[1]

There is an important constraint on the reheating temperature for the above mechanism to work. The large Hubble-induced mass term disappears after the reheating, and so, the decay rate of the χ, Γ_χ, should satisfy $\Gamma_\chi \ll O(0.1)m_Z$, where $m_Z \sim O(10)m_{3/2}$ is the modulus mass. This inequality is satisfied for the reference values, $m_{3/2} \sim 100$ GeV and $T_R \sim 10^9$ GeV. When the Hubble-induced mass term disappears at the reheating, the potential minimum is expected to change accordingly. One may think that the modulus oscillations are then induced afterwards. However, the modulus continues to follow the minimum during and after the reheating since its mass scale is larger than the Hubble parameter at that time, as long as the above inequality is satisfied. We have numerically checked that the modulus amplitude is indeed suppressed enough to solve the moduli problem, taking account of the effect of reheating.

It has been known that, for the gravitino LSP of mass $m_{3/2} \sim 100$ GeV, the next-to-lightest SUSY particle (NLSP) is long-lived and decays into the SM particles and the gravitino during big bang nucleosynthesis (BBN), which alters the light element abundances in various ways [14,15]. The BBN constraints on the NLSP can be avoided if the R-parity is not an exact symmetry, but explicitly broken by a small amount [16,17]. Such R-parity violation may be ubiquitous in the string landscape [18]. In order to not erase the baryon asymmetry, the size of the R-parity violation is constrained [19,20]. There is a certain range of parameters where the NLSP decays well before the BBN while the baryon asymmetry is not erased. Note that the gravitino is long-lived because of the Planck suppressed interactions even if the R-parity is broken, and therefore becomes dark matter. The gravitino decay may leave some signature in the cosmic-ray spectrum [16,17,21,22], which may be discovered in the future indirect dark matter search.

Lastly let us consider an implication for inflation models. With the cut-off scale of the theory below the Planck scale, the inflaton mass easily exceeds the Hubble parameter during inflation, because of the following operator,

$$\mathcal{L} = -\int d^4\theta\, \frac{|\phi|^4}{\Lambda^2}, \tag{8}$$

where ϕ denotes the inflaton. Namely, the η-problem gets worse than usual [3]. This problem can be circumvented if the inflaton mass is protected by symmetry, such as the shift symmetry. Indeed there are such models that the inflaton mass is forbidden by symmetry [23–26].

We have assumed that the gravitinos are mainly produced by thermal scatterings. On the other hand, the gravitinos are known to be non-thermally produced by the inflaton decay [27,28], and such non-thermal gravitino production should be suppressed. This places upper bounds on the inflaton mass and the vacuum expectation value (VEV). One successful inflation model is a chaotic inflation model with a discrete symmetry. In this model, the inflaton mass is protected by a shift symmetry, and the inflaton and its companion field have vanishing VEVs because of the Z_2 symmetry [23]. Therefore the model avoid the η-problem and the non-thermal gravitino production does not occur.

So far we have not specified the origin of the low cut-off scale. If all the matter fields including the MSSM sector is confined on the three-dimensional brane while the extra dimensions are compactified with a typical radius larger than the higher-dimensional Planck length M_*, the four-dimensional low-energy effective theory has a cut-off scale M_*, which is lower than the four-dimensional Planck scale. We identify the cut-off scale Λ with the higher-dimensional Planck length M_*. Alternatively, there might be strong dynamics near the Planck scale, which results in a large coupling rather than the low cut-off scale, as proposed in Ref. [3].

To summarize, we have proposed that the fundamental cut-off scale Λ of the theory is lower than the Planck scale M_p, and have shown that this gives an explanation for why the SUSY particles have escaped the detection so far. The typical SUSY scale can be pushed into the TeV region, which ameliorates the constraints of the flavor-changing and CP violation processes. The gravitino is the LSP of mass $m_{3/2} \sim 100$ GeV, and accounts for the observed dark matter abundance. The requirement of successful thermal leptogenesis plays an important role to reach the above conclusion.

There are interesting implications. The BBN constraints on the NLSP can be avoided if the R-parity is explicitly broken. Then the gravitino dark matter is unstable and decays into the SM particles, which may leave observable signature in the cosmic-ray spectrum [17,21,22]. The R-parity violation may be also seen at LHC [29]. The inflation model should be such that the inflaton

[1] The operator $\frac{\langle\Sigma\rangle}{\Lambda} W_\alpha W_\alpha$ violates the GUT unification of gauge coupling constants if $\Lambda < 0.1M_p$. Here, the Σ is the adjoint **24** representation of $\text{SU}(5)_{\text{GUT}}$.

mass is protected by symmetry. One example is the chaotic inflation with a discrete symmetry. Because of the rich implications, our proposal can be tested by collider, dark matter experiments as well as the CMB observation in the near future.

Note added

As mentioned in the text, we have found that the following inequality must be met for the Linde's solution to the moduli problem to work:

$$m_{3/2} \gtrsim 100\ \text{GeV}\left(\frac{T_R}{2\times 10^9\ \text{GeV}}\right)^2. \tag{9}$$

Thus, if we require that the leptogenesis is the source of the baryon asymmetry, T_R must be higher than 2×10^9 GeV [11], which then leads to a lower bound on the gravitino mass, $m_{3/2} \gtrsim 100$ GeV. Therefore the soft SUSY breaking masses are pushed into the TeV region or heavier (see Eq. (4)), which explains why the SUSY particles have not been discovered to date. If the above inequality is not satisfied, the modulus would dominate the energy density of the Universe and produces huge entropy at the decay, which dilutes the pre-existing baryon asymmetry. Since the suppression of the modulus amplitude is exponentially sensitive to the above condition, this argument provides us with a sharp lower bound on the SUSY breaking scale.

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